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CYCLONE-ELECTROTHERMAL METHODS OF PROCESSING
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[Tsiklonno-elektrotermicheskiye sposoby pererabotki
mednogo i polimetallicheskogo syr'ya]

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Izdatelstvo "Nauka" Kazakhskoy SSR, Alma-Ata
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This volume contains articles summarizing the results of investigations of processing the copper and polymetallic concentrates and other products of nonferrous metallurgy by the cyclone method. The results of theoretical studies of the technology of cyclone smelting of sulfide concentrates are also included. Certain structural features of a cyclone facility for direct-flow and separated outflow of the smelting products and of gas are described. Also, technological characteristics are given for smelting of copper concentrates of Central Kazakhstan, industrial concentration products of the lead-zinc ores, and oxidized materials.

The material in this volume will be of interest to scientists, workers in metallurgical plants who investigate methods of processing sulfide concentrates in pulverized form, and to instructors and students in the institutions of higher learning.

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THE BASIC CONSTRUCTIONAL AND THERMAL CHARACTERISTICS
OF THE CYCLONE SMELTING UNITS

A. V. Tonkonogiy, I. A. Onayev, V. V. Vyshenskiy
and E. Balfanbayev

Since 1951, the Kazakh Institute of Energetics and the Institute of Metallurgy and Concentration of AN Kazakh SSR have jointly carried out theoretical and experimental studies of the cyclone method of smelting pulverized ores and concentrates.

These studies have shown [1 — 4] that, due to specific aerodynamics and high temperatures developed in the working chamber, the cyclone chambers ensure a high intensity of thermal and technological processes. Moreover, the cyclone chambers ensure good dust removal from the flue gases, since they work on the same principle as centrifugal dust removers with a wet film (scrubbers).

Such features of the cyclone method account for the effectiveness of its application to solve a broad range of technical problems. As examples, we can mention here the work on the cyclone smelting of pyrophosphates (the Moscow Institute of Energetics, the Research Institute of Fertilizers and Insectofungicides, the Institute of Chemical Sciences AN Kazakh SSR), and the production of high quality cement clinkers in cyclone chambers (Yuzhgiprotsement), etc.

To utilize fully the potential of the cyclone energotechnological process, it is necessary to solve a whole number of problems connected with burning fuel which is heavily ballasted with a furnace charge; with loading into the melting chamber of the cyclone an increased amount of solid phase per unit volume of the gas-air stream; and with other specific conditions arising when the process is carried out. The study of such a complex set of questions required the initiation of certain theoretical tasks [4 — 7] and a considerable number of experimental investigations on the laboratory and pilot plant scale [2 — 4, 8 — 11]. At the present time, a number of research institutes and project organizations are dealing with problems of the application of the cyclone method to processing various ores. In this connection, it will be appropriate to take the results of several investigations performed by us and, by generalizing these results, to clarify certain problems connected with the construction of a cyclone unit and with the choice of working conditions which would ensure the given parameters of the technological process.

Description of the Chamber

One of the most important factors which distinguish the work of a cyclone smelting chamber from the conventional furnace is increased weight concentration of the solid phase per unit volume of the carrier gas stream (4 — 5 times larger than in the usual furnace). Correspondingly, there is an increased amount of the obtained melt. Under such conditions, the horizontal placement of the chamber is unacceptable because of difficulties connected with removal of the melt, as was shown in our investigation [12]. When the smelting is carried out in a horizontal cyclone, the molten mass accumulates in the lower part of the chamber. This behavior deforms the aerodynamic profile of the chamber, leads to large losses of dust, and altogether to the total disruption of the established working conditions. As a result, the burning of fuel and the melting of material become displaced outside of the cyclone chamber. In the long run, the chamber becomes converted into a conventional burner. All these reasons, as well as the results of a thorough investigation of the work of vertical cyclone chambers,

lead to the conclusion that cyclone chambers should be placed only vertically, and should be equipped with a flat diaphragm. These measures facilitate a more uniform distribution of the melt along the generatrix of the cyclone, and ensure its easy outflow.

Smelting cyclones can work only using a slag-hardened caisson lining, since the lifetime of conventional refractories is limited to several days only. The composition of coating for the slag-hardened lining should be selected depending on the chemical composition of the ore to be smelted. For deposition of coating, the internal surface of the cyclone chamber is covered with dowel pins. The height of the pins, their diameter and distribution (spacing) are chosen in conformity with recommendations of the All-Union Thermotechnical Institute.

In processing some materials, not all the physico-chemical transformations comprising the process are done in the cyclone. Depending on the requirements of the technological process, the cyclone chamber can be combined with a settling reservoir. This reservoir serves for the completion of chemical reactions, accumulation of the melt, and its division into the slag and matte. As was found in experimental-industrial tests [3, 11, 12], when the cyclone is located directly above the molten tub, rotation of the liquid melt occurs and, as a result, there is a fast abrasion of the side walls of the settling reservoir. To prevent the rotation of the melt, caused by the stream of gases thrown out of the cyclone, it is necessary to place a water-cooled altar directly under the outlet jet (Figure 1a). The construction of the altar, which accepts the gas stream and absorbs a considerable part of its kinetic energy, prevents the rotation of the melt which is in the reservoir, improves conditions for its separation into slag and matte, and — to a large degree — reduces the wear of the reservoir lining.

If there is a necessity to conduct further processing of the melt, for instance the removal of copper from slags or sublimation of volatile metals and their compounds (zinc, lead, rare metals), the cyclone chamber is coupled with an electrothermal oven into which the melt passes. In this case, a separation chamber fitted with caisson

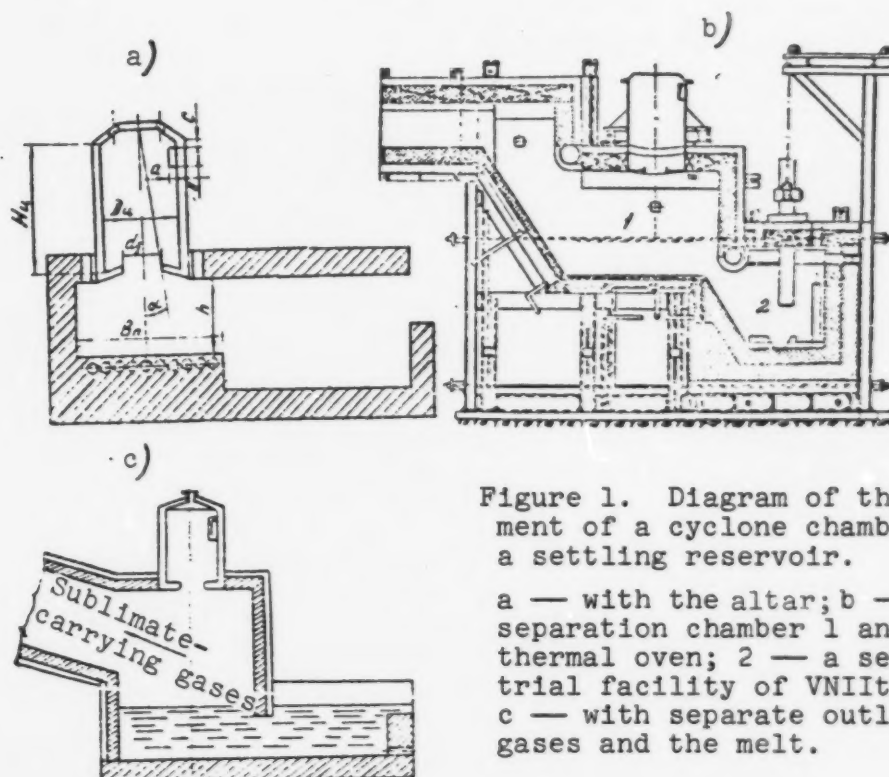


Figure 1. Diagram of the arrangement of a cyclone chamber with a settling reservoir.

a — with the altar; b — with a separation chamber 1 and electrothermal oven; 2 — a semi-industrial facility of VNIItsvetmet; c — with separate outlets for gases and the melt.

surfaces is placed under the cyclone (Figure 1b). The melt flows from this separation chamber into the electronic oven, and the gases are directed into the gas tank connected with surfaces utilizing the transferred heat.

Finally, if a raw material is processed, the melt of which has no valuable components and may be regarded as a waste product, the cyclone chamber may be connected directly with a granulating facility, where one of the known methods of granulation (water, air method, etc.) is applied. In this case, it is necessary to employ cyclone chambers with separate outlets for the gases and the melt, as was described by A. L. Tseft.

When the cyclone chamber has to be placed above the melt granulator, or above the electrothermal oven-settling tank, a quite effective measure in processing many materials is the use of a chamber with a top outlet for the gases. However, such a chamber is not considered

in this paper, since it is dealt with in a special article of the present volume [14].

Constructional Characteristics

The complexity of the working process occurring in the cyclone has prohibited the development of a sufficiently full theory of the process, on the basis of which the useful technical calculations could be performed. In this connection, an investigation was made of a series of geothermally-similar cyclone chambers, with the preservation of practically invariant values of all the characteristics of the processed ore (sulfide copper concentrates), and the thermal and technological processes. The investigations were conducted on four cyclone chambers with different internal diameters ($D_c = 0.45, 0.65, 1.0$ and 1.5 m) in a broad range of productivity per charge (from 10 to 250 tons/day). The results led to a basic relationship — the quantitative connection between the productivity and the internal diameter of the cyclone D_c (Figure 2). This relation can be expressed by the approximate equation:

$$G = AD_c^{2.5}, \text{ tons/hour} \quad (1)$$

where A — a constant equal to 3.5 — 3.7 for smelting of sulfide copper concentrates, and 2.5 for sublimation processes.

It is appropriate to point out that relation (1) agrees well with results of theoretical studies and the accepted scheme of the process [6]. According to this scheme, thermal processing of the ore charge, as well as burning of a solid fuel in the cyclone chamber, take place both in and on the walls of the chamber, covered with a film of the melt ($G \sim D_c^3$, for the process occurring within it, and $G \sim D_c^3$ for the process taking place on a film of the melt).

The dependence (1) establishes the diameter of cyclone chambers for a given productivity of the unit. This internal diameter proves to be the basic parameter in calculations for cyclone chambers.

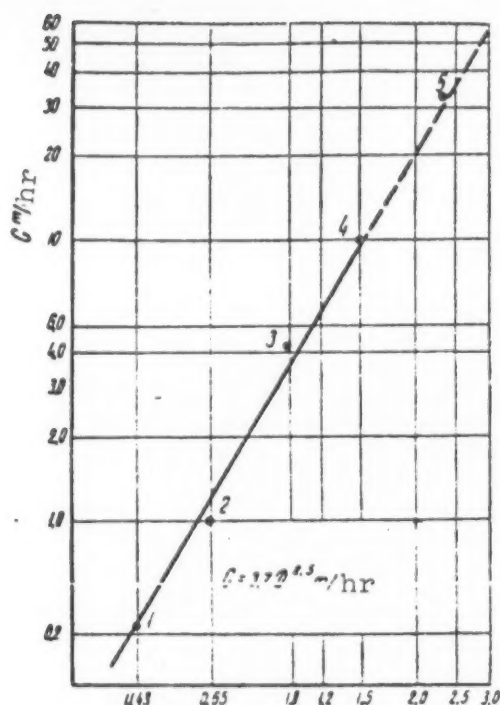


Figure 2. Changes of cyclone chamber productivity in processing copper sulfide concentrates depending on the diameter of the chamber.

1 — the cyclone facility of KazNIIenergetics; 2, 3 — the facility of OSZ VNIItsvetmet (3 — two-sided entrance of air); 4 — semi-industrial facility of BGMK; 5 — experimental-industrial facility of BGMK.

which sublimates of metals are condensed, due to the phenomena of adhesion and sorption. Additional separation of suspended particles occurs when the stream of gas makes contact with the altar and the walls of the forechamber. Then, the melt becomes enriched with the metal, which leads to an increase of its losses with slag and to a reduction of the technological indices of the sublimation process.

Special investigations of the rules governing the propagation of the curled stream and the experimental stand melts [15, 11] established the effect of forechamber constructional parameters on technological indices of the cyclone process. With increasing distance of the

Other geometrical relations in a cyclone should be chosen as depending on its diameter. We know also from operational tests of the cyclone smelting chambers that the diameter of the outlet diaphragm should be chosen in the range $d_c = (0.38 - 0.45)D_c$; and height of the cyclone chamber $H_c = 1.3 - 1.7) D_c$.

In the variant of the cyclone chamber with an altar and a settling reservoir (Figure 1a), the altar together with the walls dividing it forms a forechamber of the settling reservoir. During the pyroselection in the cyclone under the action of a high temperature and appropriate gas medium we have, apparently, not only the sublimation of volatile metal oxides, but also the volatilization of reduced metals. In this way, the gaseous stream emerging from the cyclone contains vapors of metals and their oxides and also fine solid particles of the charge of ore, onto

cyclone diaphragm from the altar, there is a decrease of the axial component of the average velocity v_z of the force of impact of the gaseous stream against the altar, and concurrently, a decrease of the losses of metal with the slag. For various investigated materials, a certain average velocity of the impact of the stream against the altar, v_z , is permissible. The distance of the altar from the diaphragm is calculated from the given permissible value of v_z according to the following relation:

$$h = \frac{d_d}{\operatorname{tg} \alpha} \sqrt{\frac{0,54 D_C^2}{v_z d_d^2} \cdot \frac{T_g}{T_0 - 0,5}}, \quad (2)$$

where T_g — temperature of gases at the outlet from the cyclone;

α — the angle of opening of the gaseous stream at the outlet from the cyclone; this angle is equal to $15 - 17^\circ$ for a flat diaphragm.

In the calculations, it is necessary to take the fact into account that, with increasing distance of the altar and a decrease in the additional recovery of waste from the cyclone, there is also a reduction in the enrichment of sublimates. For this reason, we can recommend an optimal value of the distance of the altar from the diaphragm of $h - (3 - 5) d_D$.

The minimum width of the altar should be equal to the value:

$$D_A = d_D + 2h \operatorname{tg} \alpha. \quad (3)$$

Dimensions of the settling part of the reservoir are determined from the required time of settling and chamber productivity.

The recovery coefficient of liquid slag and melt in the cyclone chamber amounts to about 90%, without taking into account the sublimation during volatilization processes.

When an oxidizing process is carried out — for instance, smelting of copper sulfide concentrates — the calculation of the expected expenditure of air should use the total air excess coefficient equal to $\alpha = 1.05 - 1.1$. Here we consider the burning not only of carbonaceous fuel, but also of solid fuels contained in the ore charge.

When carrying out a sublimation process requiring a reducing medium, the amount of air needed is determined from the given composition of gases, relative to the output from the cyclone chamber. In the latter case, it is necessary to consider also losses arising from the incomplete mechanical combustion, $Q_4 = 3 - 5\%$.

The lowest temperature of the air preheating supplied to the cyclone should be 450°C .

The cyclone chambers of diameter larger than 1 m should be equipped, at least, with two diametrically opposed, tangential air inlets. The optimal rate of supplying the air into the cyclone is $120 - 130 \text{ m/sec}$. However, the total cross section area of the air nozzles is chosen to provide a certain reserve, so that at the nominal output of the chamber and at fully opened regulating valves, the rate of supplying the air into the cyclone is $80 - 90 \text{ m/sec}$ (sic).

The configuration of the air nozzles is chosen so that their width a is within the limits: $a = (0.08 - 0.1) D_c$.

The aerodynamic resistance of the cyclone chamber ΔP is determined from the relation:

$$\Delta P = 6,9 \rho v_{in}^2 \left(\frac{F_{in}}{F_{out}} \sqrt{\frac{D_c}{H_c}} + 0,03 \right), \quad \text{mm H}_2\text{O} \quad (4)$$

where ρ and v_{in} — density and velocity of air at the inlet to the cyclone;

F_{in} and F_{out} — total area of cross section of air nozzles, and the area of cross section of the outlet opening of the diaphragm.

The fuel to be burned in the chamber should be introduced into the air nozzles (before the cyclone) at some distance before their apertures. This ensures the preliminary heating of the fuel and its good mixing with air — resulting in a steady ignition of the jet at the cyclone inlet, and the development of a high temperature in the upper part of the chamber. This is extremely important, since in smelting cyclones the charge loaded into the working area of the chamber acts as a ballast during the burning of the jet, and can reduce significantly the intensity of the thermal process. This scheme of supplying the fuel to a considerable degree prevents the ballasting effect of the charge (see also [14]).

Heat Balance

To calculate the expected expenditure of fuel, and correspondingly of air, it is necessary first to set up the heat balance according to the equation:

$$Q_1 = Q_T + Q_B = Q_2 + Q_3 + Q_4 + Q_5 + Q_6 + Q_7 + Q_8 - Q_9 + Q_{10}, \quad (5)$$

- where
- Q_T — heat of combustion of the fuel and of combustibles in the charge;
 - Q_B — heat brought in by the preheated air;
 - Q_2 — heat taken away by smoke and gas from the cyclone;
 - Q_3 and Q_4 — losses due to the chemical and mechanical incomplete combustion;
 - Q_5 — losses of heat in water cooling the walls of the chamber;
 - Q_6 and Q_7 — heat taken away by the melt and sublimates;
 - Q_8 and Q_9 — endothermic and exothermic heats of reaction;
 - Q_{10} — heat lost in evaporation of moisture in the charge.

It is most convenient to reduce the heat balance expressed in Equation (5) to the relation per unit of weight of the processed raw material.

The heat taken away by smoke and gas, Q_2 , will vary, depending on the variants considered above of the constructional grouping of the cyclone assembly.

When the assembly consists of a cyclone chamber and a settling reservoir, the temperature of gases leaving the cyclone should be chosen in such a way that the temperature at the outlet of the settling tank exceeds the temperature of the outgoing melt by approximately 100° . Here, thermal losses through the surfaces enclosing the reservoir should be taken into account.

When an electrothermal oven is employed, the temperature of gases at the outlet from the cyclone should be calculated in such a way that it covers heat losses in the separation chamber, and is by 100° higher than the temperature of the melt which enters the electrothermal part of the assembly.

In the absence of a settling reservoir, the temperature of gases at the opening of the diaphragm, or of the top of the chamber (for a cyclone with an upper outlet for gases), should exceed by $100 - 150^\circ$ the temperature of the melt which is flowing out of the cyclone.

The maintained temperature of the melt leaving the assembly is determined usually by the flowability or viscosity of the liquid melt. As was found in experiments conducted on industrial facilities, for a satisfactory removal of the melt it is necessary that the melt viscosity μ_{cp} be higher than 150 poises.

Under conditions of metallurgical production, the furnace charge is composed with a view to obtaining a slag (melt) of the optimum state with respect to its physico-chemical properties, including viscosity characteristics. Thus, these values are determined by the composition of the processed charge. A solution of the problem of flow velocity of the slag film along the wall of the cyclone chamber, and of the probable temperature of its surface [16], gives the average temperature of the melt flowing out of the cyclone:

$$t_{ep} = t_0 + \frac{1}{c} \ln \frac{\mu_0}{\mu_{ep}}, \quad (6)$$

where t_0 — temperature of liquidus (the transition of the melt into a really liquid state);

μ_0 — melt viscosity at the temperature t_0 (determined experimentally);

c — characteristic of the temperature interval, in which melting of the slag occurs from a plastic state to a truly liquid state. For "short" slags $c = 0.04$; for "long" slags $c = 0.01 - 0.02$ [13].

Thus, the temperature of the withdrawn melt, and the heat Q_6 , are calculated for each separate case, depending on chemical composition and viscosity characteristics of the melt.

In oxidizing processes, the chemical incomplete combustion Q_5 is assumed to be equal to zero.

When conducting sublimation processes, the chemical incomplete combustion is determined from the given composition of gases at the outlet from the cyclone chamber.

As was already pointed out, the cyclone method of smelting is characterized by small dust losses. Therefore, the mechanical incomplete combustion Q_4 is small and amounts to 2 — 4%. A somewhat larger value is used for sublimation processes. When calculating the heat Q_7 , carried away with the sublimates, it is necessary to add 3 — 5% of the mechanical loss to the amount of sublimates which are obtained from volatile metals and compounds contained in the charge. As far as the temperature of the discharged material (particles and sublimates) is concerned, it should be taken as approximately 100° lower than the temperature of gases which flow out of the cyclone.

The heats of endothermic and exothermic reactions Q_8 and Q_9 , as well as the heat for moisture evaporation, are calculated by generally accepted methods and procedures.

Finally, we should remark that for calculation of the heat losses through the water-cooled, noninsulated with brick, caissons of the settling reservoir and the separation chamber, the specific heat stream should be taken in the range 40 — 50 thousands kcal/m²·hour.

The greatest difficulties arise in attempts to calculate the heat absorption by surfaces of the cyclone chamber and, consequently, the loss of heat in water cooling its walls Q_5 .

Usually, following the tradition of the thermal analysis of conventional furnaces, the role of convective heat transfer is entirely neglected in thermal calculations dealing with cyclone chambers. It is difficult to agree with such an approach, since during the intense bathing of the cyclone walls by the whirl of gas, the convective component represents a considerable fraction of the total thermal current. Special investigations [9] have shown that it reaches 30%. Hence we consider it more justified to regard the thermal current from the air vortex to the surfaces of the cyclone as the sum of convective and radiative heat currents.

Calculations of the former should utilize the experimentally found [9] relation:

$$Nu_c = 0.108 K_g K_{com} \left(\frac{F_r}{F_s}\right)^{0.5} Pr^{0.4} Re_c^{0.95}, \quad (7)$$

where K_g — geometrical criterion, for values of $F_{in} \geq 0.05$,
 F_c and $d_d \geq 0.4 D_c$

$$K_g = 0.76 \left(\frac{F_{in}}{F_c}\right)^{0.93} \left(\frac{D_c}{d_d}\right)^{0.3} \left(\frac{D_c}{H_c}\right)^{0.5};$$

$\frac{F_r}{F_s}$ — the ratio of the surface of cyclone with consideration of the roughness of walls, to the smooth surface; for real chambers with heat-resistant coating this ratio is close to 2;

Pr and Re — Prandtl and Reynolds numbers for air-gas stream in the cyclone at the inflow velocity

$$(Re = \frac{v_{in} \cdot D_c}{\nu_c});$$

$K_{com} = (0.9 \sqrt{\frac{T_a \cdot T_{out}}{T_{in}}})$ — a coefficient taking into account the change of the volume of gases on combustion, in comparison with an isothermal current;

T_{in} , T_{out} , T_a — temperatures of stream at the inlet and outlet of the cyclone, and the adiabatic temperature.

From the value of Nu_c we calculate the convective thermal current to the walls of the cyclone chamber:

$$q_K = \frac{Nu_c \lambda}{D_c} (t_{ef} - t_m), \quad (8)$$

where λ — thermoconductivity coefficient of gases;

t_{ef} — effective temperature in the cyclone $t_{ef} = \sqrt{T_T \cdot T_{out}} - 273$;

T_T — theoretical temperature of combustion.

Calculations dealing with the radiant heat current can be carried out according to the TsKTI method, described by B. D. Katsnelson [17].

From the melting temperature of the charge t_{ch} , we determine the coefficient of thermal effectiveness ψ of the lined walls of the cyclone, taking into account the reradiation of the surface of liquid film:

$$\psi = 0.53 - 0.25 \frac{t_{ch}}{1000} \quad (9)$$

From the value of the assumed air excess α , we find the coefficient β , which takes into account the use of the theoretical temperature of the radiation source, instead of the actual temperature:

$$\beta = 0,2 + 0,7\alpha. \quad (10)$$

From the temperature of gases at the outlet of the cyclone T_{out} , we find the attenuation coefficient

$$K = 1,6 \frac{T_{out}}{1000} - 0,5. \quad (11)$$

The length of the light ray in the chamber [18] is

$$l = \frac{0,9D_c H_c}{H_c + 0,5D_c} \quad (12)$$

The effective degree of blackness of the flame [19] is

$$e_f = m(1 - e^{-Kpl}), \quad (13)$$

where m — space factor of the chamber with the flame, which can be taken as equal to unity for cyclone chambers;

p — pressure in the chamber.

From Equations (9) and (13), we find the degree of blackness of the chamber

$$\epsilon_T = \frac{e_f}{e_f - (1 - e_f)\psi}. \quad (14)$$

From Equations (9), (10), (14) and the theoretical temperature of combustion T_T , we can calculate the specific thermal sensitivity of the cyclone walls with regard to the radiant heat current:

$$q_r = 4,9 \cdot 10^8 \left(\frac{T_T}{1000} \right)^4 \text{ Kcal/m}^2 \cdot \text{hour}. \quad (15)$$

During our investigations of the processing of various ores on stand cyclones and semi-industrial and experimental-industrial cyclone facilities, we studied the heat balance when solid and liquid fuels were employed and under various imposed thermal conditions of the chambers. We found that the specific sensitivity of lined surfaces of the cyclone lies in the range $(80 - 120) \cdot 10^3$ kcal/m²·hour, which agrees well with results obtained from Formulas (8) and (15), and can be recommended for use in calculations of the thermal loss Q_s . The upper limit of the given value should be used in processing high-melting materials, when the temperature of gases leaving the cyclone should be maintained at the level of 1500 — 1550° C.

Conclusions

High intensity of thermal and technological processes, efficient dust removal from smokes and gases, and complex processing of the ore, are among the reasons for effective utilization of cyclone chambers for melting, burning, calcination and sublimation of a broad range of materials in nonferrous and ferrous metallurgy, chemical industry, and others.

Generalization of the results of theoretical studies, and of experimental work carried out on the laboratory, stand, semi-industrial and experimental-industrial cyclone facilities, as well as the operational tests of industrial cyclone assemblies, provided a number of basic constructional and thermal parameters for cyclones. They are described in this article. These parameters can be recommended for planning the new, and reconstructing the existing, cyclone chambers.

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